VA-3092-003-02-TR

SERDP PROJECT CU-1121 FINAL REPORT

PROCESSING TECHNIQES FOR DISCRIMINATION BETWEEN BURIED UXO AND CLUTTER USING MULTISENSOR ARRAY DATA

April 2002

PERFORMING ORGANIZATION

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This research was supported wholly by the U.S. Department of Defense, through the Strategic Environmental Research and Development Program (SERDP) through Project CU-1121 under Contract DACA72-99-009.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **APR 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Processing Techniques for Discrimination Between Buried UXO and Clutter Using Multisensor Array Data**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **AETC Inc.,1225 Jefferson Davis Hwy, Suite 800,Arlington,VA,22202**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**40**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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1. Project Background

This project has addressed the issue of discriminating between buried unexploded ordnance (UXO) and clutter in the context of environmental cleanup. With traditional survey methodology ("Mag and Flag" methods with hand-held detectors operated by explosives ordnance disposal (EOD) or civilian UXO technicians), the Army Corps of Engineers finds that 85-95% of all detected objects are not UXO.

In the last decade, modern UXO detection surveys conducted with digital systems and geo-referenced positioning have consistently demonstrated superior detection capabilities over "Mag and Flag". However, in spite of the recent advances in UXO detection performance, false alarms due to clutter still remain a serious problem. Because the cost of identifying and disposing of UXO in the United States using current technologies is estimated to range up to $500 billion, increases in performance efficiency due to reduced false alarm rates can result in substantial cost savings.

Unlike clutter, which can have any shape and composition, UXO are typically long and slender and are composed of a steel body with a brass or aluminum fuze body and copper driving bands. These physical attributes produce distinctive signatures in electromagnetic induction (EMI) sensor data. This project was aimed at systematically exploring the performance improvements that may be realized using EMI sensors when distinguishing target attributes are included in the discrimination process, amid contribution from competing signal sources under field conditions.

2. Project Objectives

The overall objective of this project was to develop reliable techniques for discriminating between buried UXO and clutter using multisensor EMI array data. The goal was to build on existing research that exploits differences in shape between ordnance and clutter by including the effects of other distinctive properties of ordnance items (fuze bodies, driving bands, fin assemblies, etc.). Specific project objectives were to (1) elucidate underlying physical principles relating to the electromagnetic response of ordnance items, (2) determine fundamental physical limitations on ordnance/clutter discrimination using multisensor survey data and (3) devise effective multisensor processing schemes to discriminate between buried UXO and clutter using broadband EMI data.

3. Technical Approach

The technical approach used to attain the objectives consisted of five major elements (Table 1).

1	Fully characterize ordnance electromagnetic induction (EMI) spectra.
2	Determine appropriate basis functions and implement them in UXO signature models.
3	Develop parameter estimation procedures for fitting UXO signal models to multi-axis spectra.
4	Assemble a clutter signature library.
5	Establish decision rules for UXO/clutter discrimination and evaluate their performance.

Table 1. The five major elements in the overall technical approach

During the first year's efforts to characterize the EMI spectra from ordnance, a large body of data was collected on UXO and other test objects (spheres and cylinders). These data were organized into an easily accessible database, which is available for download from the SERDP ftp site [1]. This database may be useful to the UXO community in its own right, separate from our work toward the overall project goal.

This database was used to develop a signal model that efficiently describes the EMI response. We based the ordnance signature characterization on the magnetic polarizability tensor, which was determined by measuring the induced dipole moment with different target orientations. We determined the complex eigenvalues of the polarizability tensor as a function of frequency; the Geophex GEM-3 sensor used in this project has a usable bandwidth from 30 Hz to 24 kHz. We decomposed the polarizability tensor into a basic response that depends only on the permeability, aspect ratio, and ratio of size to skin depth, and a residual response that includes the effects of body shape and constituent elements. We expressed the residual response as a sum of basis functions that are simple forms (sphere, ring, plate).

This signal model was then used to invert the data and estimate the model parameter values. Parameter estimation procedures for both data inversion and target discrimination were developed. Modified steepest descent techniques were developed for fitting models to data.

In order to understand the clutter, a large number of EMI spectra were obtained for representative clutter items recovered in excavations at various sites, including several Native American Lands (Badlands Bombing Range, Laguna Pueblo, Walker River, etc.) and the DARPA clutter sites (Ft. A. P. Hill and Ft. Carson).

In order to determine the fundamental limits to discrimination, various sources of error were investigated, including position errors, non-dipole effects and inherent variability in the UXO themselves. For the last, EMI spectra were obtained for a several hundred 60mm and 81mm ordnance items recovered from Jefferson Proving Ground, Indiana (see section 5.8).

The database was expanded to include both the clutter and the UXO EMI spectra; the library will help establish decision rules for UXO/clutter discrimination and evaluate their performance.

Finally, all results were drawn upon to find reliable algorithms for UXO discrimination. This includes decision rules for discriminating between UXO and clutter using multidimensional vectors based upon estimated target parameters. However, the enlarged library of UXO spectra showed a large statistical spread in the model parameters for 60mm and 81mm ordnance, due to the inherent variability of the UXO themselves; this would make discrimination more difficult. There were also indications, however, of patterns in this parameter spread, which might be useful for discrimination. More data and analysis are required. The final decision rules will be determined in the follow-on project, UX-1313, funded by SERDP.

4. Summary

During the first year of the project, we focused on signature characterization to evaluate whether or not the ordnance-unique content in the EMI spectrum is strong enough to be measured in the presence of ground conductivity and other competing effects. Using the GEM-3 sensor, we collected and analyzed the EMI spectra for baseline shapes (steel cylinders and spheres) and comparable ordnance items as functions of range and orientation, and determined the complex eigenvalues of the polarizability tensor as a function of frequency from 30 Hz to 24 kHz. The baseline spectral data were synthesized into a parametric model that depends on three nondimensional parameters: length to diameter aspect ratio, relative permeability, and the ratio of diameter to skin depth. Using this model for the EMI response from cylindrical objects, we established that real ordnance objects produce unmistakable deviations from this model that are more than an order of magnitude greater than deviations due to other competing effects (e.g., ground conductivity). These results were documented in the 1999 annual report [2] and presented to the community at several conferences [3,4,5,6].

During the second year of the project, in addition to improved calibration and evaluation of the GEM-3 sensor, we substantially expanded the library of EMI measurements taken in the laboratory with the GEM-3. We made measurements on a wide variety of clutter objects and also made measurements of targets (both signature and clutter) at several orientation angles (pitch and roll) and horizontal spatial locations relative to the sensor. The library was expanded to well over 250,000 individual measurements on a wide range of items and all the additional data were added to the Microsoft Access database on the SERDP web site. We expanded our baseline EMI response model to describe UXO with rotating bands (also called driving bands) and found that fitted parameters of this model with the driving band extension show clear separation between objects with driving bands and those without, suggesting a new capability in UXO discrimination [7].

We made progress characterizing non-dipole effects, which are a source of modeling error. Our model assumes that the target response to the primary field of the sensor is an induced point dipole located at the target center, but the true EM response is governed by the interaction between the primary field and the full three-dimensional target, over which the primary field may vary significantly. Data analysis performed during this year showed that simple physics-based correction terms are not sufficient, and a goal for the following year was to determine purely empirical correction terms for this effect. This work was documented in the annual report for 2000 [8].

In the third year, with the now-mature models, we started the model synthesis and data inversion necessary to extract the model parameters from EMI field data for target discrimination. We developed, tested and refined several model inversion techniques. Papers were presented at numerous conferences throughout the year, describing our model and its potential for discrimination [10,11,12,13,14,15,16]. Two papers describing the model, phenomenology and utility were published in an IEEE peer-reviewed journal [17,18].

We also developed data processing algorithms for UXO/clutter discrimination. For this, we completed our investigation of non-dipole effects, developed a clear understanding of their magnitude relative to other factors, and developed an empirical model to account for these effects. Having determined that a significant amount of variability in derived parameter values is related to non-dipole effects, we then developed a simple algebraic correction to help remove these errors. The correction factor, which is based on simple terms that reflect the degree of non-uniformity of the primary field, improves model accuracy and consistency of derived parameters for simple targets of uniform composition and simple shape, but turned out to be much less effective for more complicated shapes. This work is documented in section 5.4 and in the annual report for 2001 [19].

Since our standard model is limited to highly permeable objects, we developed an empirical model that can address low permeability targets. This model [20] matches a wide range of targets with arbitrary permeability and arbitrary shape, including spheres, a 41mm projectile and a tangle of wire. We also reconciled the time domain and frequency domain EMI signature models; this work was published in a peer-reviewed journal [21].

The final step in our project was to develop effective decision rules, or classifiers for discriminating UXO from clutter. These rules operate on target-specific statistics derived from EMI survey data and generate predictions as to whether or not a given target is UXO. In an ideal noise-free environment, with no measurement or navigation errors, all UXO of a given type would produce statistics that coincide at a single point in parameter space and the decision rule would consist of this point only, resulting in perfect predictions. In real-world environments, errors cause derived parameters to form a cloud, and this cloud overlaps points associated with clutter objects. The decision rule must be expanded to encompass the entire cloud of UXO points but, in doing so, it also encompasses clutter points that become false positives and degrade discrimination performance. In this environment, the optimal decision rule directly depends on the particular distribution of the UXO cloud, and performance directly depends on the size of the cloud. To improve discrimination performance we must 1) minimize the size of the UXO cloud, and 2) learn its distribution with some accuracy.

We approached this problem by investigating the causes of parameter dispersion, and then using that information to guide development of robust statistics to better resist dispersion under field conditions. We have found in this project that dispersion has three root causes: 1) modeling errors, 2) measurement errors, and 3) variability in the UXO themselves [19]. There is a difficulty here because the last two factors change markedly from site to site. Measurement errors, for example, include positioning errors, and these are very different at flat, open sites compared to uneven, wooded ones. Likewise, variability among the UXO themselves changes from site to site. Therefore, the contribution to dispersion from these factors changes from site to site, and this greatly complicates the problem of defining an optimal decision rule. Nevertheless, we proceeded by focusing on target features that are invariant across the vast bulk

of UXO, and which we felt could be measured fairly reliably. We defined statistics for aspect ratio (AR) and axial symmetry (AS) based on measured EMI signals; these statistics were presented in detail at the UXO/Countermine Forum in 2001 [22]. We applied these statistics at the Jefferson Proving Ground Technology Demonstration (JPGTD) in 2000 with mixed results. For some targets, our statistics corresponded well to the ground truth, but for many others they did not.

We analyzed our performance using a Monte Carlo simulation that included a realistic noise model. Typical field data contain positioning errors from differential GPS, errors from possible timing differences between the sensor GPS and data streams, and errors from sensor motion during the integration time window. We have found that these errors create multiple local minima in the parameter space of our models, and these minima can hinder the fitting and target identification process. We investigated performance of different inversion schemes in terms of computation requirements and ability to find global minima in the presence of positioning errors [8]. We concluded that positioning error in the horizontal plane was the most significant measurement error contributor to parameter dispersion, and hence to our mixed performance with JPGTD data. This study was presented as a talk and poster at the 2000 SERDP Symposium [9].

To better understand the third underlying cause of parameter dispersion, target variability, we coordinated with the Army Environmental Center's SERDP project UX-1300, Standardized Test Sites, and gained access to 250 fired and certified inert 60mm and 81mm mortar rounds from Jefferson Proving Ground. We made careful measurements on these UXO items to estimate the magnitude of inherent variability. Results showed variability to be quite significant and also revealed underlying patterns in the EMI signatures that could be associated with specific target attributes, such as a shroud on the tail fins. From this analysis, documented in [22], it became clear that inherent UXO variability represents a significant and fundamental limit on discrimination schemes, and also an important input for optimization of these schemes. Decision rules must account not only for dispersion of parameters due to deformed and/or deteriorated UXO, but also variability in design and manufacture within each ordnance type. This problem calls for a detailed investigation that is beyond the scope of this project. The required research has already been proposed and funded by SERDP as a follow-on project, UX-1313.

Project Accomplishments

4.1. Identifying Ordnance-Unique Signature

Electromagnetic induction occurs when a time-varying primary magnetic field is established over a buried conducting target. In response to the primary field, eddy currents develop within the target, producing a secondary magnetic field that can then be measured at the surface. The secondary field depends on the size, shape, composition, and orientation of the target. For frequency domain electromagnetic instruments, the measured data consist of the amplitude and phase shift of the secondary field.

The EMI response for a given target depends on (1) the relative position and orientation of the sensor and the target, (2) the frequency of the primary field, and (3) the shape and composition of the target. Previously, an EMI response model for compact (i.e., small enough to ignore shape and size) conducting objects had been developed [23]. This model was used successfully to invert EMI data [24] in order to estimate target specific information. This model exploits the fact that the secondary field may be accurately described as a dipole field in which total response is a linear combination of the response from each principal axis of the target. Using this approach, EMI data collected over a spatial array surrounding the target may be analyzed to estimate the orientation and aspect ratio of the target.

This project analyzed EMI spectra and showed that the distinctive attributes of the ordnance (aspect ratio, composition, driving bands, etc.) produce unique signatures in the EMI data. This, together with the strength of the response, can be used on laboratory and test data to identify and discriminate the target. These unique ordnance signatures have been documented in the annual report for 1999 [2], have been presented at numerous conferences [3 through 6; 11 through 15], and are described briefly in section 5.3 below.

4.2. Database of Ordnance and Clutter EMI Signatures

To determine which factors are critical for EMI-based discrimination, a forward mathematical model and an empirical set of UXO signature and clutter data are required. The empirical data were collected in a controlled environment in order to isolate all the factors.

The sensor used for all measurements in this project was the GEM-3 (Figure 1) manufactured by Geophex Ltd. [25]. The GEM-3 employs a pair of concentric circular coils to generate the primary magnetic field. Current runs in opposite directions in the two transmit coils, thereby setting up a zone of magnetic cavity at the center where the primary field strength approaches zero. A receiving coil placed within this magnetic cavity senses the weak secondary field resulting from eddy currents in the buried target. All coils are molded into a single circular disk in a fixed geometry and precisely known dimensions. This frequency-domain instrument makes measurements at several discrete frequencies ranging from 30Hz to 24kHz.

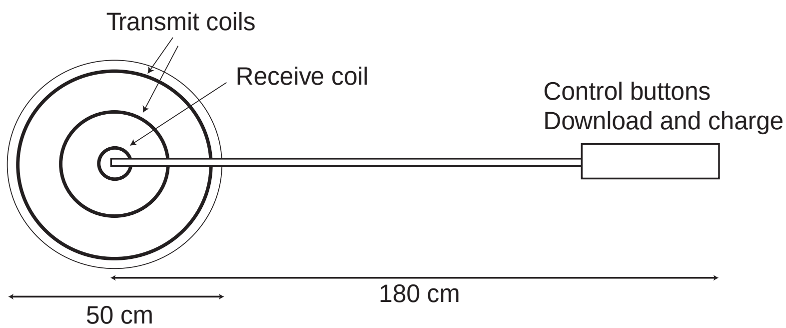

Figure 1. Top view (plan) of the GEM-3 instrument.

By using a fixed sensor, an all-wooden frame stand and target jig and standardized targets (Figure 2), we were able to isolate effects of low signal-to-noise ratio, errors in sensor or target location, ground eddy currents, and non-dipole effects. Later, computer calculations simulated the results of navigation errors, optimization algorithms, computer speed and performance.

Figure 2. The GEM-3 instrument was set up to measure test objects under controlled conditions. This pictures shows a 3-inch diameter steel ball being tested.

We measured the EMI response for a wide range of test objects (Figure 3) including UXO, spheres, cylinders, and clutter. We compiled more than 250,000 individual measurements, representing each object at several distances, orientations, and conditions. The methodology and results are documented in the 1999 annual report [2] and in a SERDP In-Progress Review [3].

Figure 3. A variety of test objects were measured to investigate the capabilities of the GEM-3 and to provide a basis for analysis.

These data are available in the Microsoft Access database at the SERDP ftp site [1]. The database includes measured EMI response, object dimensions, shape, composition, orientation, and all relevant distances. Background measurements and measurements on wire coils and ferrite rods are also included to allow proper calibration of the instrument. A querying tool is included that searches through all the data tables to find data for a given object. Another tool is also provided in the database that downloads all data to text files so they can be read normally by other software.

4.3. Development of Forward EMI Response Models

4.3.1. Calibration with Spheres

As a first step toward developing mathematical expressions to describe aspects of EMI data collected with the GEM-3, we analyzed the agreement between our measured data and the analytical solution for the response of a metal sphere in a spatially uniform, time-varying primary field. The sphere model was fit to EMI data from several metal spheres ranging in diameter from 5/8 inch to 5 inches. The metals included chrome steel, stainless steel, aluminum, bronze and brass. For all cases, the agreement between the GEM-3 data and the model was within about 1 percent at frequencies below 1 kHz and within about 0.1 percent for frequencies above 1 kHz.

The sphere model used is for the case of a spatially uniform primary field. An analytic solution is also available for the case of a dipole primary field, which may be a better approximation of the primary field generated by the GEM-3. That solution is more complicated, consisting of a summation of terms representing dipole, quadrupole, octopole and higher components. However, the excellent agreement found between the uniform-field model and GEM-3 data indicated that the higher order terms may be safely ignored for the dimensions and geometries used in this study. (Since higher order terms fall off more rapidly with distance, it follows that the dipole term should dominate as distance increases; measurements in this data set were collected with the sphere generally farther than one diameter length away from the sensor.)

Fitted model parameters for the 3-inch chrome ball were compared against published values. Values for the exact metal in our sample were not found in the literature, so similar metals were used for comparison. The fitted value for relative permeability compares with values extrapolated from literature sources for similar metals. The fitted value for conductivity also compares with values for similar metals (Table 1).

	Conductivity (mho/m)
Estimate for our sample	1.82 E 6
Plain carbon steel type AISE-SAE 1020	1.0 E 7
Stainless steel type 304	1.39 E 6

Table 1. The estimated conductivity for the 3-inch steel ball compares well with published values for similar metals. Source: CRC Handbook of Chemistry and Physics p. D-171 (Weast, 1976 [26]).

These results show that the GEM-3 instrument is capable of producing data that accurately match analytical solutions, and that leads to parameter estimates that compare well with known values. More importantly, this provides a valid starting point for development of more general models to describe important aspects of EMI response of arbitrary (i.e., non-spherical) objects. These calibration results are documented in an annual report [2] and were presented at a SAGEEP conference [6].

4.3.2. Standard Model and Analyses

The model for the metal sphere was used to develop a baseline model for EMI response of arbitrarily shaped conducting objects. The resulting 3-parameter model fits a wide range of objects extremely well. In most cases, fitted parameters agree reasonably well with expected values. The basic model and the analyses described below are documented in [2], were presented at many conferences [3 through 6; 10 through 16], and are described in detail in a journal article [17].

Analysis of EMI response from cylinders revealed artifacts that depend on the ratio of skin depth to wall thickness of hollow objects. Differences in EMI response arose when the skin depth approached the wall thickness of the hollow cylinder. The frequency at which the model and data curves diverge agrees well with the frequency calculated from the skin depth.

We found a consistent pattern of response for cylinders of arbitrary size, but common length-to-diameter aspect ratio. By concatenating graphs for different sized cylinders but identical aspect ratio, we developed "type curves" to describe this pattern, providing insight for further refinement of our model. These type curves validated the appropriateness of the baseline model and provided insight for objects of similar aspect ratio.

We gained an understanding of how ferrous material alters the overall EMI response by introducing a ferrite rod into a copper cylinder. At high frequency, the copper pipe/ferrite rod combination behaves like a copper pipe alone. This is expected because eddy currents at the copper surface cancel out all magnetic fields inside the object. At low frequency, we would expect the copper pipe/ferrite rod combination to behave like the ferrite rod alone, since the magnetic field penetrates through the copper without interference. The data suggested that this occurred, although the measurable frequency range of the GEM-3 does not go low enough to confirm it positively.

We also investigated the different responses due to small shape changes of the target. We measured, for different orientations, the response of a cylinder with and without a small point cut into one end. The observations show no statistical difference in EMI response for the different shapes, and therefore give no chance to discriminate between them. This represents a limitation of the technology; for objects with subtle variations in shape such as these, EMI is not going to be capable of resolving differences under field conditions. However, other features of typical UXO produce very strong EMI response, which appear to be promising for discrimination, as described in the next section.

4.3.3. Modeling the Driving Bands

Driving bands are soft metal rings near the tail of a projectile designed to make sliding contact with rifling grooves in the gun bore when the projectile is fired. They are typically made of copper and found on a wide variety of projectile types and sizes. Analysis of the EMI data revealed that the driving bands are responsible for a large artifact in the overall response of many projectiles [7]. This fact offers a promising tool for target discrimination since driving bands are found on UXO but not on clutter objects.

We were able to produce EMI signals very similar to that from a projectile with a driving band by using a steel pin with a copper loop around it. The contribution from the copper loop was assessed by measuring the signal from the separate components (Figure 4). The figure plots the in-phase and quadrature response data (circles) versus frequency; the lines are the fit to the dipole model. The copper loop alone produces a relatively weak response, but when placed around the steel pin, it produces a strong feature in the overall EMI response that is particularly easy to detect and identify. The location of the peak in the quadrature curve is related to the size of the copper loop, leading to the possibility that the projectile caliber may also be determined from this artifact. In order to match the data from projectiles with driving bands, the model was expanded to a 5-parameter model. This model is described in detail in the 2000 project annual report [8] and an IEEE journal article [17].

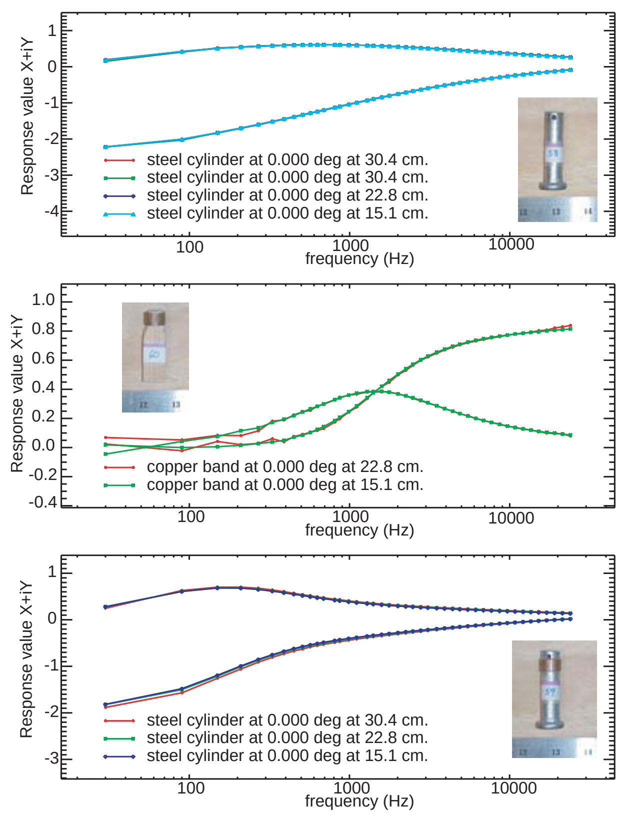

Figure 4. Top: response of a steel cylinder. Middle: response of a copper band. Bottom: response of the copper band on the steel cylinder. The amplitudes have been normalized to evaluate the shape of the response. The copper loop alone produces a relatively weak signal compared to its influence when it interacts with the steel pin.

4.3.4. Modeling Targets with Arbitrary Permeability

The models presented to this point are limited to highly permeable objects. In this regime, the primary field has a relatively small penetration depth into the body of the target, leading to a simplified EMI response characterized by a symmetrical peak in quadrature. This regime was investigated analytically by Kevin O'Neill in another SERDP-funded project, resulting in analytic solutions for EMI response of high permeability spheroids where the small penetration depth (SPA) approximation holds [27]. Our empirical models also reflect the simplified nature of EMI response in this regime, evidenced by the fact that very good fits to data can be made with a small number of parameters.

We have developed an empirical model to address low permeability targets, a regime that has proven difficult to model numerically and analytically for arbitrarily-shaped targets. This model arises from the observation that the analytic solution for the sphere can be expressed in the same form as the analytic solution for an infinite horizontal cylinder, where the solutions differ by one in the order of the Bessel functions. We hypothesized that other shapes might be matched using the same form but with a Bessel function of different order. By making the order of the Bessel function a fit parameter, we discovered we could get excellent matches to a very wide range of targets, with arbitrary permeability and arbitrary shape; examples are shown in Figure 5. This model was presented at the 2001 SERDP In-Progress Review meeting [20].

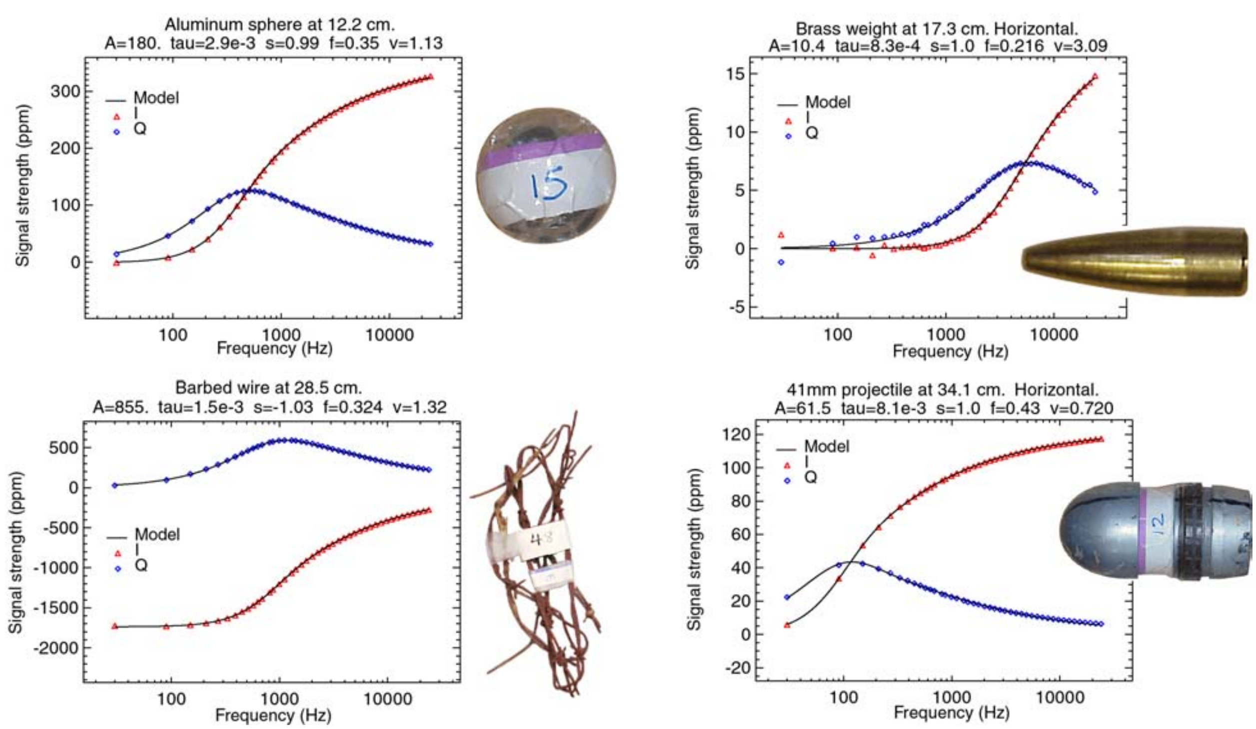

Figure 5. EMI response from a wide variety of targets with arbitrary permeability can be modeled using the 5-parameter model arbitrary-permeability model.

4.4. Modeling Error Due to the Non-Dipole Effect

Our model is based on the assumption that the secondary field emanating from the target is that of a point dipole [18]. This is an important limitation of the model since real targets, especially large UXO located close to the sensor, exhibit significant non-dipole contributions to the overall response. These produce modeling errors, resulting in greater dispersion of derived statistics in parameter space, and hence degraded discrimination performance.

We developed a clear understanding of their magnitude of these non-dipole effects relative to other factors [8,19]. Then, to reduce these errors, we developed empirical correction factors to the target response coefficients (beta values) along the target's principal axes. Each of the three correction factors (one for each principal axis) is a dimensionless real-valued scalar, ranging between 1 and about 10. They depend on target dimensions, and on the sensor/target geometry.

Our method of computing these correction factors is motivated by the observation that large targets near the sensor generate more response than predicted from the dipole model. We attribute this to the fact that the dipole model predicts response based on the excitation field (primary field) located at the center of the target, a by-product of the assumption that the target acts like a point dipole located at the target center. In reality, regions within the body of the target that are closer to the sensor, where the primary field is stronger, contribute disproportionately to the overall EMI response, making the measured response larger than predicted.

The correction factor is determined along each target axis separately, using the same algorithm. For the longitudinal axis, we find the maximum primary field strength in the longitudinal direction, over all points within the body of the target, and divide this value by the primary field strength in the longitudinal direction located at the center of the target. Terms for the other principal axes are found similarly. These correction terms are close to 1 for very small targets, and range up to 10 or more for large UXO-sized objects. They depend on target orientation in the primary field, and on the specific shape and dimensions of the target. The actual factor applied to response coefficient (beta value) of each axis is

$$\beta_c = \beta_o \left[(A_1/A_2 - 1)\, f + 1 \right]$$

where A_1 and A_2 are the primary field amplitudes along the axis at the maximum value and at the center of the target, and the factor f is found by regression over the data. The value for f is on the order of 0.5.

Due to a scarcity of the required spatial laboratory data, we were only able to derive and test the coefficients on one set of data, collected with a cylinder. Figures 6 and 7 show the improved fit realized from the correction formula. In each figure, the collection of graphs represents a dipole model fit to EMI data collected at several spatial points over the fixed target. The large region on the right shows a plan view over the target, where data from each point in the test grid are plotted in a separate, small graph centered over the corresponding data collection point. In each small graph, the red represents the in-phase response and the blue the quadrature; the black lines show the dipole model fit. Beta values for the target were derived from test stand data; these are

shown on the left. In Figure 6, it is obvious that the dipole fit is very poor at many of the spatial. However,

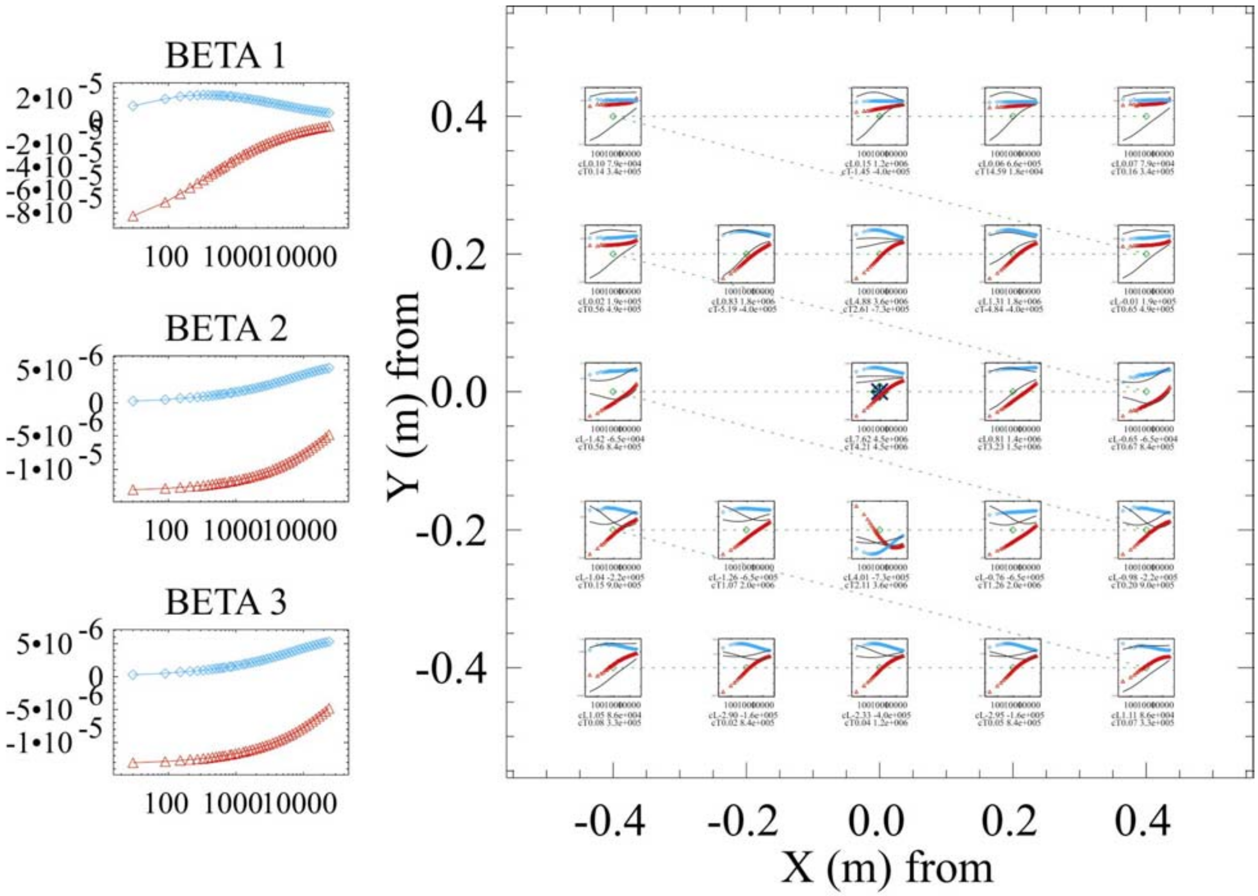

Figure 6. Dipole model fits to EMI data collected at different spatial locations around a fixed cylindrical target.

Figure 7 shows the same dipole model fit, but with correction terms applied. These corrections give much improved agreement with the measured data.

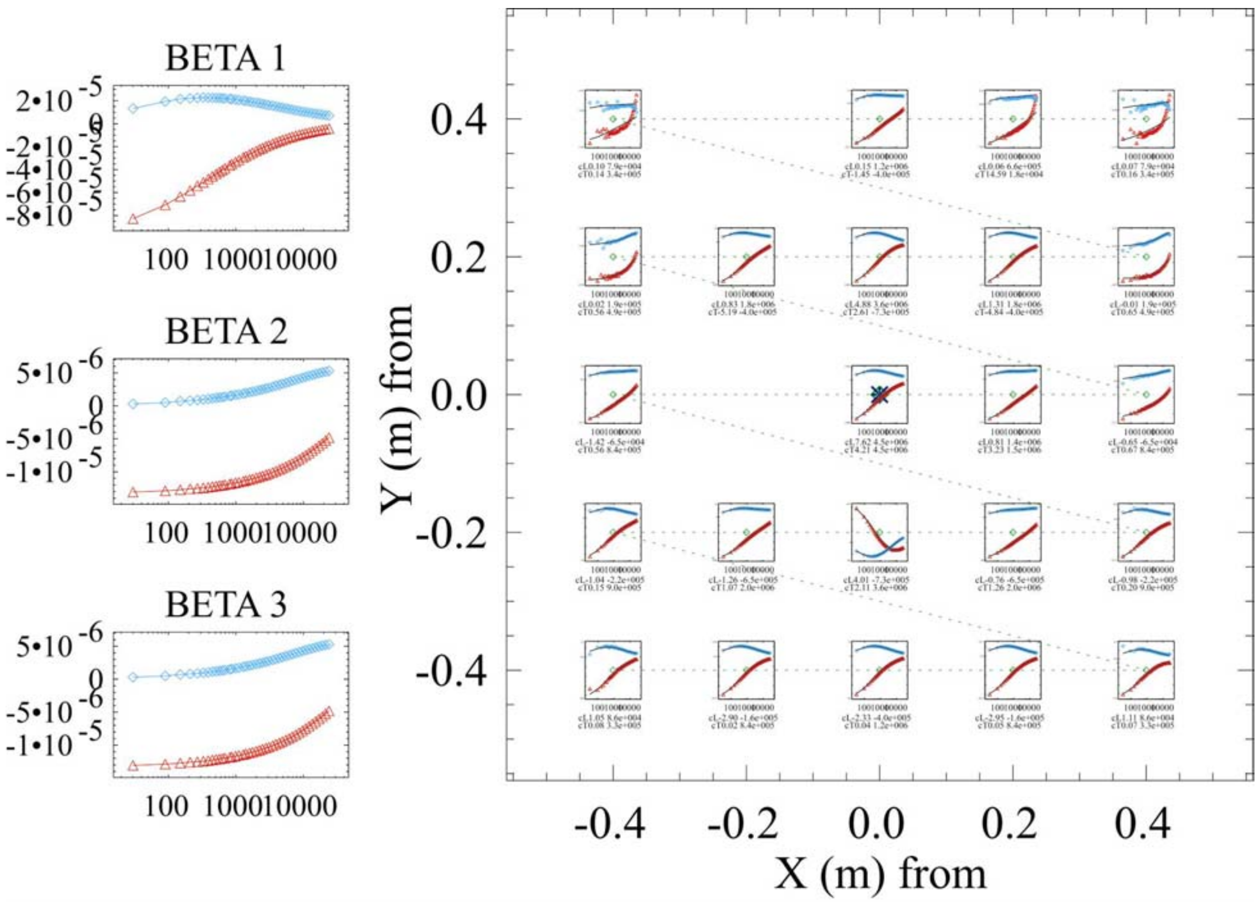

Figure 7. Dipole model fits to the same data shown in Figure 6, with non-dipole correction terms applied.

When this method was applied to data from UXO objects, results were much less accurate. We believe that is due to interaction between the different material properties of the components (e.g., body and fins) of the UXO, compared to the uniform composition of our steel cylinder test samples. Our conclusion is that this correction factor is effective for simple targets of uniform composition and simple shape (cylinders), but much less effective for more complicated shapes.

4.5. Evaluation of Signal Distortion Error

We evaluated four additional sources of signal distortion: the presence of conducting ground, non-uniform material properties of the object, target surface condition, and temperature. We determined that, under the worst case, the most severe effect was the non-dipole effect described above in the previous section; this would cause about 6% distortion in the signal spectral shape (Table 2). These results were presented at a SERDP In-Progress Review [3] and in a poster session at a SERDP/ESTCP Symposium [4].

Conducting ground effects	< 5%
Non-dipole effect	Up to ~6% for large objects.
Inhomogeneous material composition	< 1%
Target surface (rust, paint)	< 1%
Temperature (over a range of ~30 °C)	< 1%

Table 2. Several effects that could potentially interfere with UXO discrimination were evaluated.

At the same time, we determined that much larger differences than these were measured as a result of switching targets. In particular, the difference between a 37-mm projectile and a cylinder of roughly the same size (Figure 8) was about an order of magnitude larger than any of these effects above. The frequency-dependent structure of the difference was reproducible and consistent over a range of depths.

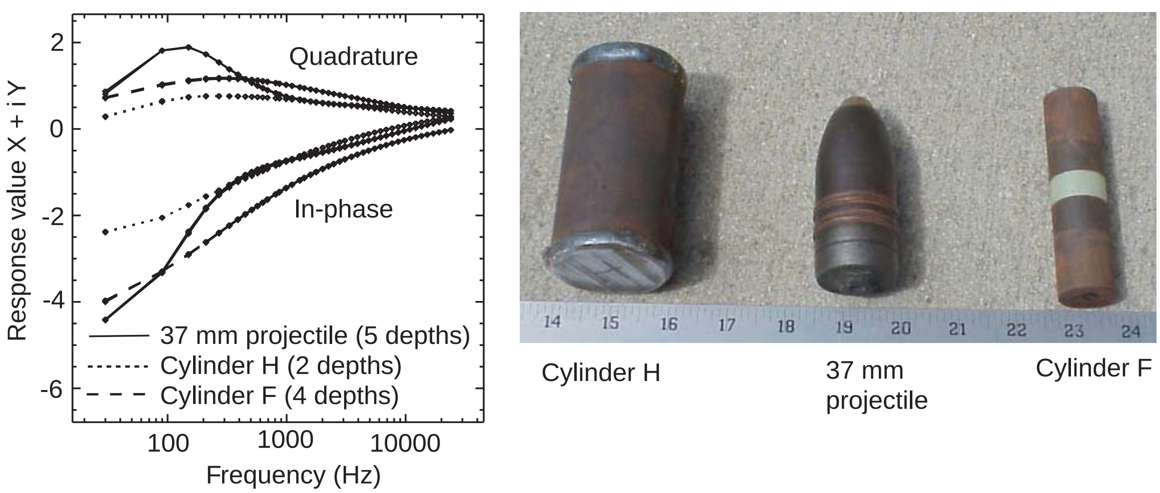

Figure 8. EMI response from the 37mm projectile shows strong differences from response of similarly sized cylinders. This difference is consistent over a range of depths, and it is about an order of magnitude larger than any competing effect.

4.6. Feature-Based Characterization of UXO-Like Targets

Effective decision rules, or classifiers for discriminating UXO from clutter, operate on target-specific statistics derived from EMI survey data and generate predictions as to whether or not a given target is UXO. In an ideal noise-free environment, with no measurement or navigation errors, all UXO of a given type would produce statistics that coincide at a single point in parameter space and the decision rule would consist of this point only, resulting in perfect predictions. In real-world environments, errors cause derived parameters to form a cloud, and this cloud overlaps points associated with clutter objects. The decision rule must then be expanded to encompass the cloud of UXO points, but in doing so, it also encompasses clutter points that become false positives and degrade discrimination performance. This decision rule framework is discussed in [9].

We investigated the causes of parameter dispersion, and found that there are three root causes: 1) modeling errors, 2) measurement errors, and 3) variability in the UXO themselves. There is a difficulty here because the last two factors change markedly from site to site. Measurement errors, for example, include positioning errors, and these behave very differently at flat, open sites vs. uneven, wooded ones. Likewise, variability among the UXO themselves is different from site to site. Therefore the contribution to dispersion from these factors changes from site to site, and this greatly complicates the problem of defining an optimal decision rule.

Nevertheless, we proceeded by focusing on target features that are invariant across the vast bulk of UXO, and which we felt could be measured fairly reliably. We defined statistics for aspect ratio (AR) and axial symmetry (AS) based on measured EMI signals [22]. These statistics were based on the fact that UXO items are generally long and slender with circular cross section and length to diameter aspect ratios from 2:1 to 5:1. These features distinguish them from some clutter objects, and produce simple patterns in parameters derived from field data. These parameters, the axial symmetry statistic and the aspect ratio statistic, are based on the eigenvalues of the magnetic polarizability tensor [17, 18, 22].

We applied these statistics at the Jefferson Proving Ground Technology Demonstration in 2000 with mixed results. For some targets, our statistics corresponded well to the ground truth, but for many others they did not. We attributed the relatively poor results to errors in measurement (including navigation) but were also concerned about the effect of inherent variability of the UXO themselves on the fitted parameters.

4.7. Effects of Positioning Errors

The measurements made with the GEM-3 for developing the standard model were performed under controlled conditions in a laboratory. However, field measurements involve motion of the sensor during data collection, as well as errors in navigation and subsequent location of the measurement points. Typical field systems using differential GPS experience horizontal positioning errors around $\pm$ 5cm and vertical errors around $\pm$ 10cm. There may be additional positioning errors due to timing differences between the sensor data stream and GPS data stream.

These positioning errors affect how accurately the data can be inverted to extract the model parameters. We studied this with a simulation; we produced 6000 random realizations of the target location and orientation, and then calculated expected signals from a GEM-3 sensor at several "true" survey locations for each realization. The resulting synthetic data sets were input to our inversion algorithm to see how closely we could recover the original target configuration (for an 81 mm mortar round). The synthetic data were corrupted intentionally to simulate real-world survey conditions; errors were inserted into the z position of the sampling locations, into the x and y locations, into the sensor noise (i.e., a white noise process), and into the time difference between the GPS and the EMI time stamps. The error levels were also varied.

Since positioning errors create multiple local minima in the parameter space of or models, we performed a mini-study on optimization algorithms to find an effective algorithm. Three algorithms (simulated annealing [28], downhill simplex [29], and downhill simplex with three restarts) were used for the calculations. A total of four reduced-noise cases were run, each based on the baseline case with one (only) noise source reduced by half. A final case was run with zero noise of any kind to confirm that the original target configuration is recovered exactly under these conditions, as expected. Figure 9 shows the results. For these cases, the downhill simplex gave the best answer; for other situations, however, the simulated annealing can take longer but produce a better fit in the end [20].

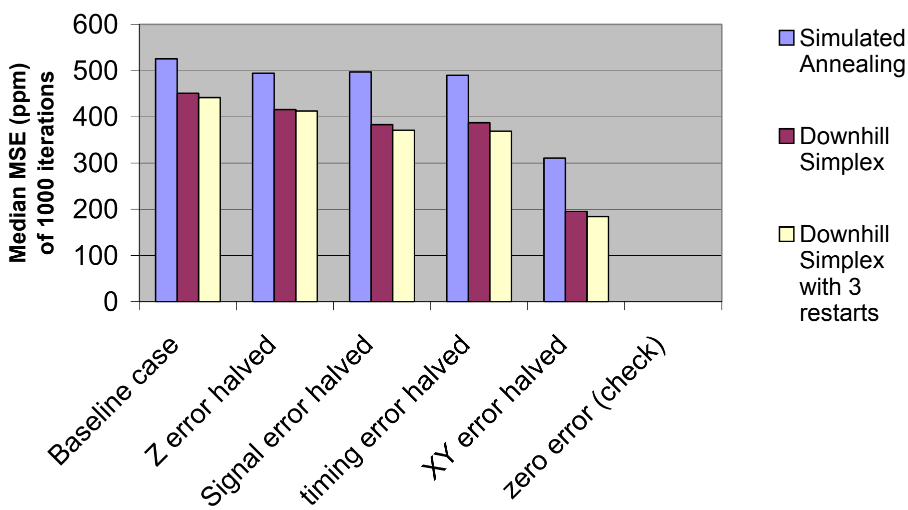

Figure 9. Of the four error sources modeled, reduction of horizontal x-y position errors produced the largest improvement in agreement with the model.

We also examined the effects of target depth on algorithm performance, and found that reducing horizontal position errors by half reduced fitting errors by more than one half for several depth categories (Figure 10). This may be attributable to statistical fluctuations since we had 11 depth categories (bins in the histogram), so each would be expected to have just 91 events on average. Without knowledge of the underlying distribution, however it is not possible to establish accurate error bars on the histogram.

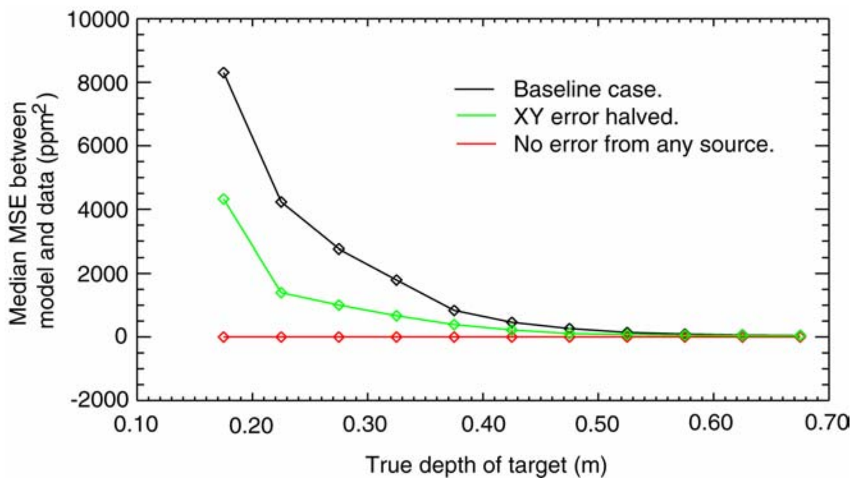

Figure 10. Effect of horizontal x-y position error with target depth.

An important conclusion is that horizontal (x,y) measurement errors are the most serious contributor to degraded model fits. These results are documented in the project annual report for 2000 [8] and were presented at an annual SERDP/ESTCP Symposium [9] and a SERDP In-Progress Review [20].

4.8. Effects of Inherent Variability of UXO

The last phase of the project investigated the inherent variability in the electromagnetic induction (EMI) response among a number of similar UXO. We had previously discovered that physical deformations and alterations within a single UXO type (i.e., 60mm) appreciably change the EMI signals. This is a problem because a sample UXO item will be visually classified "UXO" regardless of the physical deformation and model, but its EMI signature may not. Variability of similar-type UXO represents both a fundamental limit on the best possible performance of all EMI-based discrimination schemes, and also an important input for optimizing such schemes.

To address this issue, we made arrangements to quantify EMI signal variance for 125 60mm and 125 81mm UXO that will be utilized during the ESTCP-sponsored project entitled "Standardized UXO Technology Demonstration Sites" (Mr. George Robitaille, US Army Environmental Center). After identifying, photographing and measuring the UXO (Figure 11), we collected broadband EMI response data with the same GEM-3 sensor and the same methods used for the other measurements for this project. For these variability measurements, the target was positioned directly below the sensing coils in three orientations relative to the primary field: namely, long axis of the UXO parallel (nose up and nose down) and transverse.

Figure 11. Left: 60mm (foreground) and 81mm (background) ordnance after cataloging. As shown in the right hand photograph, some of the individual UXO are rather intact, while others are severely deformed and fragmented.

The work performed on inherent variability of UXO is documented in detail in the annual report for 2001 [19]. Figures 12 and 13 summarize some of our findings. The figures show the usual

response curves but normalized so that each spectral sweep covers the same vertical span, in order to compare shape.

Ideally, if all the UXO were indeed identical (and measurement errors are negligible), the spread in frequency response curves would be contained within a single line width for each primary orientation. Figure 12 presents frequency spectra for a number of measurements of a single 60mm UXO when the target was oriented parallel to the primary field (top) and transverse (bottom). It is clear that an ideal target provides repeatable and identical responses.

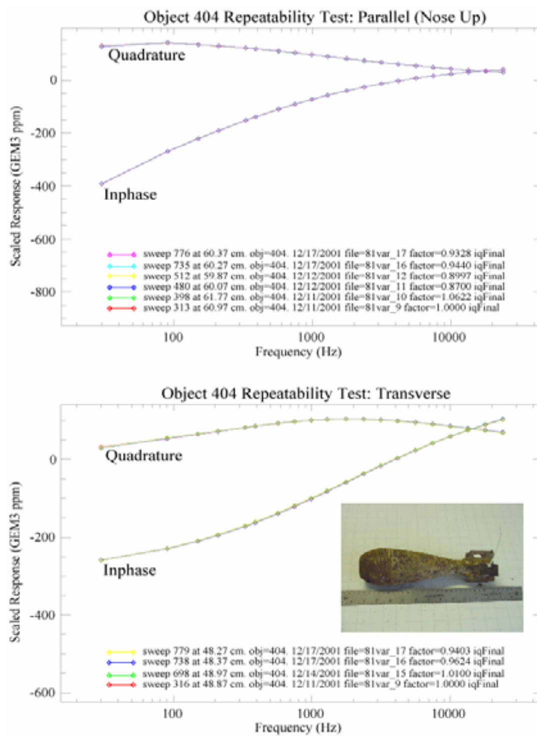

Figure 12. Repeat EMI measurements of a sample 60mm (Object #404). The two plots represent different sensor-target distances, with the long axis of the target aligned parallel (top) and transverse (bottom) to the primary field.

It is also reasonable to expect distinct sets of curves if the UXO have configurations involving different – but finite – sets of fins, fuse, or body styles. Numerous measurements were taken of sets of 60mm and 81mm UXO at various orientations and for various groupings of UXO: training rounds only, practice rounds only, illumination rounds only, smoke rounds only, UXO with and without tail fins, fuses and shrouds. Each set contained significant scatter in the responses. However, it also became apparent that certain shape patterns in the response are associated with particular components of the UXO [19].

Figure 13 shows the variability measured for two sets of practice 60mm UXO models – with and without a tail boom. In the figure, red is nose up, yellow is nose down, and blue is horizontal. (The primary field was vertically aligned during all measurements.) The gray curves represent all data - all targets and all sensor-target orientations - for these 60mms.

Two primary sets of curves are readily apparent in Figure 13. In comparison to practice 60mm UXO without tail booms, the presence of the tail boom increases the frequency associated with the peak quadrature response and significantly changes the in-phase response.

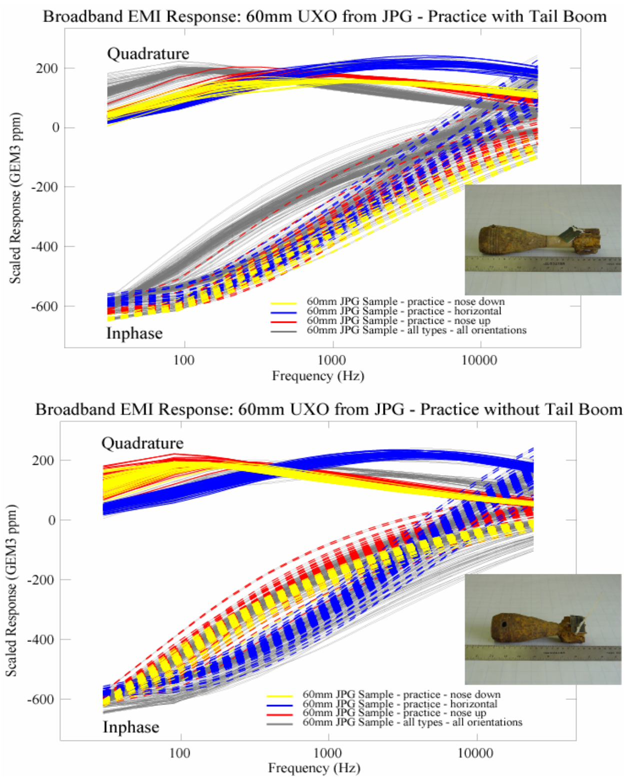

Figure 13. Significant variability is observed in the broadband EMI response for the 60mm UXO. In these plots, colors indicate orientation and line styles indicate in-phase or quadrature components. Two distinct sets of curves are observed depending on the presence of a tail boom.

It became clear from this analysis of only a few ordnance types that inherent variability in the UXO must be accounted for in the final decision rules for UXO/clutter discrimination. Because the rules must not only include enough logic to allow for deformed objects, but must represent all possible models of a given UXO type, this analysis requires study outside the scope of this project.

5. Conclusions

The objective of this project was to develop reliable techniques for discriminating between buried UXO and clutter using multisensor electromagnetic induction (EMI) array data. In the course of this project, we have developed models for ordnance-unique signatures in EMI response spectra, and developed data inversion techniques for extracting the model parameters from EMI field data. The final step in our project was to develop effective decision rules, or classifiers for discriminating UXO from clutter. These rules operate on target-specific statistics derived from EMI survey data and generate predictions as to whether or not a given target is UXO. We defined statistics for aspect ratio (AR) and axial symmetry (AS) based on measured EMI signals and applied these statistics at the Jefferson Proving Ground Technology Demonstration in 2000 with mixed results. For some targets, our statistics corresponded well to the ground truth, but for many others they did not.

We attribute these results to dispersion in the derived parameter values, caused by a combination of model errors, measurement errors, and inherent variability of the UXO themselves. Our computer simulations of various noises showed that positioning error in the horizontal plane was the most significant measurement error contributor to parameter dispersion. A limited analysis of inherent variability of 60mm and 81mm mortars from Jefferson Proving Ground showed that this source of error is also quite significant.

It became clear that inherent UXO variability represents a significant and fundamental limit on discrimination schemes, and also an important input for optimization of these schemes. Decision rules must account not only for dispersion of parameters due to deformed and/or deteriorated UXO, but also variability in design and manufacture within each ordnance type. This problem calls for a detailed investigation that is beyond the scope of this project. The required research has already been proposed and funded by SERDP as a follow-on project, UX-1313.

6. Transition Plan

The modeling results of this research project have been transitioned to the community as the research was performed. The database of EMI laboratory measurements on ordnance, standard objects, and clutter is on the SERDP website and is available for download by any researcher. Our theoretical and empirical results have been presented at the SAGEEP and UXO/Countermine Forums, and have also been published in peer-reviewed journals.

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Appendix A Technical Publications

Peer-Reviewed Journal Papers (in separate electronic files)

Miller, J.T., T.H. Bell, J. Soukup and D. Keiswetter, 2001, "Simple Phenomenological Models for Wideband Frequency-Domain Electromagnetic Induction." *IEEE Transactions on Geoscience and Remote Sensing*, 2001, Vol. 39, No. 6, p.1294.

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Bell, Thomas, Bruce Barrow, Jonathan Miller and Dean Keiswetter, 2001, "Time and Frequency Domain Electromagnetic Induction Signatures of Unexploded Ordnance.” *Subsurface Sensing Technologies and Applications,* Vol. 2, No. 3, July 2001.

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Keiswetter, D., I.J. Won, J. Miller, T. Bell, E. Cespedes and K. O’Neill, 2000, “Electromagnetic Induction Spectroscopy for Detecting and Identifying Buried Objects,” Detection and Remediation Technologies for Mines and Minelike Targets V, Orlando, Florida, 24-28 April, 2000, Proceedings of SPIE, Vol. 4038.

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Won, I.J., D. Keiswetter, T. Bell, J. Miller and B. Barrow, 2000, "Electromagnetic Induction Spectroscopy for Landmine Identification," Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Arlington, Virginia, February 20-24, 2000; Conference Proceedings, pp. 801-809.

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FEATURE–BASED DISCRIMINATION OF UXO/CLUTTER USING BROADBAND ELECTROMAGNETIC INDUCTION: DEVELOPMENT OF EMPIRICAL FORMULAS

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8. *Abstract Category:* DETECTION

The electromagnetic induction (EMI) response of a conducting target at arbitrary orientation in the primary field can be approximated as a linear combination of responses associated with each principal axis of the target, corresponding to eigenvalues of the magnetic polarizability tensor. Unexploded ordnance (UXO) have certain characteristic features, such as axial symmetry and consistent length to diameter aspect ratio, which produce simple patterns in these eigenvalues and these patterns may be used to distinguish them from clutter objects. We define statistics that reflect the presence or absence of UXO-related patterns in eigenvalues calculated from spatially referenced EMI data. We demonstrate performance of these statistics on synthetic data both under zero-noise conditions and also several cases with different levels of realistic noise added in. Results show that these statistics can effectively discriminate between UXO and clutter, however performance depends on both the magnitude of noise in the data and on the orientation and depth of the target.

Presented at the UXO/Countermine Forum, April 9-12, 2001, New Orleans, LA.

CHARACTERIZATION STUDIES OF THE ELECTROMAGNETIC INDUCTION RESPONSE OF COMPACT METALLIC OBJECTS FOR IMPROVED UNEXPLODED ORDNANCE/CLUTTER DISCRIMINATION

B. Barrow, T. Bell, J. T. Miller

Currently, most unexploded ordnance (UXO) remediation is carried out with magnetic and electromagnetic induction (EMI) sensors. While highly effective in detecting metallic objects such as UXO, present field techniques also result in many false targets from metallic scrap. To reduce the cost of digging non-UXO, discrimination techniques using both current and future EMI technologies are needed. Using both frequency domain (FD) and time domain (TD) instruments, a variety of controlled measurements have been made over a large range of test objects including spheres, cylinders, plates, inert UXO, and scrap. In most cases, the response can be reasonably modeled as an induced dipole moment. The strength and direction of this moment is determined by the relative strength of the transmit field along the major symmetry axes of the object. The strength of the responses along the principal axes is a function of frequency for FD sensors and a function of time for TD sensors. Indeed, the time response can be shown to be a simple convolution of the frequency response with the fourier transform of the TD transmit pulse. For spheres, all axes are the same and the measured response functions match analytic solutions found in the literature. For axisymmetric, ferrous objects such as cylinders and most UXO, there are two independent response functions to consider: along the symmetry axis and orthogonal to this. For ferrous cylinders, the scaling of these functions with size and aspect ratio has been empirically determined as a function of frequency and the functional form of these curves can be related to the analytic solution for a ferrous sphere. Surprisingly, the response of most UXO and a variety of metal scrap can also be fit to this functional form. To some extent, these curves can be used to discriminate between UXO and clutter given significant differences in the shape and size of the objects concerned. These curves can be inverted from careful measurement over an unknown object, but careful spatial positioning is required.

Presented at the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Arlington, Virginia, February 20-24, 2000; Conference Proceedings, pp. 819-828.

ELECTROMAGNETIC INDUCTION SPECTROSCOPY FOR DETECTING AND IDENTIFYING BURIED OBJECTS

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Abstract

An object, made partly or wholly of metals, has a distinct combination of electrical conductivity, magnetic permeability, and geometrical shape and size. When the object is exposed to a low-frequency electromagnetic field, it produces a secondary magnetic field. By measuring the broadband spectrum of the secondary field, we obtain a distinct spectral signature that may uniquely identify the object. Based on the response spectrum, we attempt to "fingerprint" the object. This is the basic concept of Electromagnetic Induction Spectroscopy (EMIS). From numerous surveys that we have conducted using our multifrequency electromagnetic sensors (GEM-2 and GEM-3), we have accumulated significant evidence that a metallic object undergoes continuous changes in response as the transmitter frequency changes. These observations made over many UXO targets suggest strongly that the EMI anomaly measured in a broad band offers an ability to both detect and identify a target. The frequency-dependent structure of the difference was also reproducible and consistent over a range of depths. Therefore, we have established that the GEM-3 is capable of delivering broadband EMI data with ample target-specific information content for the purpose of target classification and identification.

Keywords: Electromagnetic Induction, Discrimination, Electromagnetic Induction Spectroscopy, UXO, and Identification

Presented at the SPIE, Detection and Remediation Technologies for Mines and Minelike Targets V, Orlando, Florida, 24-28 April, 2000, Proceedings of SPIE, Vol. 4038.

Presented at the UXO/Countermine Forum, Anaheim, California, May 2-4, 2000.

DISCRIMINATING CAPABILITES OF MULTIFREQUENCY EMI DATA

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Abstract

Although commercially available geophysical sensors are capable of detecting UXO at nominal burial depths, they cannot reliably discriminate between UXO and clutter. As a result, an estimated 75% of remediation funds are spent on nonproductive excavations. During the past few years, we have been studying the merits of using multifrequency EMI data for discriminating between UXO and non-UXO targets and believe the method has tremendous potential. The EMI spectral response of an object is a function of its electrical conductivity, magnetic permeability, shape, size, and orientation relative the primary exciting field. By measuring a target's spectral response, we obtain its characteristic frequency-dependent signature. Based on the response spectrum, we "fingerprint" the object and compare its response to known UXO signatures.

To explore this phenomenon, we have developed a unique, frequency-domain EMI sensor named the GEM-3, which operates over a bandwidth of 30 Hz to 24 kHz. Empirical data acquired using the GEM-3 for a wide assortment of UXO and non-UXO suggests strongly that the EMI anomaly measured in a broad band offers an ability to both detect and identify a target. We present results of controlled measurements made with the GEM-3 sensor to address the question of competing effects such as sensor stability, depth and shape effects, and inhomogeneous material properties. The frequency-dependent signatures are reproducible and consistent over a range of depths. Therefore, we have established that the GEM-3 is capable of delivering broadband EMI data with ample target-specific information for the purpose of target classification and identification.

Keywords: Electromagnetic Induction Spectroscopy, UXO, Discrimination, GEM-3, Electromagnetic Induction

Presented at the International Geoscience and Remote Sensing Symposium (IGARSS), Honolulu, Hawaii, July 24-28, 2000.

Presented at the International Conference on Subsurface Sensing Technologies and Applications, 30 July – 4 August, 2000, San Diego, California, Proceedings of SPIE Vol. 4129.

ELECTROMAGNETIC INDUCTION RESPONSE OF SPHERICAL CONDUCTORS MEASURED WITH THE GEM-3 SENSOR, AND COMPARED TO ANALYTIC MODELS

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Currently, most unexploded ordnance (UXO) remediation is carried out with magnetic and electromagnetic induction (EMI) sensors. While highly effective in detecting metallic objects such as UXO, present field techniques also result in many false targets from metallic scrap. To reduce the cost of digging non-UXO, discrimination techniques are required. One approach to UXO discrimination is to recognize features from broadband EMI data that reflect the shape of the target only, while filtering out other features which may relate to target depth, orientation, sensor-dependent signals, or combinations of these factors. A thorough calibration of the sensor against targets of known shape and material properties is required for interpretation of field data. Toward this goal, controlled measurements were made using the GEM-3 (FDEM) sensor on spherical conductors of various sizes at several distances. These data generally compare very well against the analytic solution for a sphere in a spatially uniform, time varying magnetic field, despite the fact that the GEM-3 sensor produces a primary field that is not spatially uniform. A quantitative assessment of the data shows that the dipole approximation of the induced field is valid over a wide range of operating conditions.

Presented at the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Arlington, Virginia, February 20-24, 2000; Conference Proceedings, pp.829-836.

DETECTION OF COPPER ROTATING BANDS ON BURIED ORDNANCE USING WIDE-BAND ELECTROMAGNETIC INDUCTION

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9. *Abstract Category:* DETECTION

Rotating bands are soft metal rings near the tail of a projectile designed to make sliding contact with rifling grooves in the gun bore when the projectile is fired. They are typically made of copper and found on a wide variety of projectile types and sizes. In this paper we demonstrate that rotating bands are particularly easy to detect and identify using wide band electromagnetic induction (EMI) instrumentation. Our finding is supported by a large set of data collected on a variety of objects under both controlled conditions and in the field. Rotating bands contribute a strong and distinctive signal to the overall response of an ordnance item, characterized by a relatively sharp peak in quadrature, similar to the response of a wire loop alone. We attribute this signal to a combination of three factors: 1) the relatively high conductivity of rotating bands compared with the body of the projectile, 2) the fact that rotating bands are in the shape of a loop, and 3) the capability of wide-band EMI instruments to sweep a range of frequencies, ensuring excitation of the frequencies where the rotating band contribution is strong. We find that the frequency of the quadrature peak is related to the diameter of the rotating band, which suggests this signal may be very useful in identifying targets.

Presented at the UXO/Countermine Forum, May 2-4, 2000, Anaheim, California.

EFFECTS OF POSITIONING ERRORS ON BROADBAND EMI DATA INVERSION

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ABSTRACT

Simple empirical models have been developed to analyze EMI data and provide some capability to discriminate between UXO and clutter. We use the models to invert EMI data and extract information related to the identity of the target. Typical field systems using differential GPS experience horizontal positioning errors around +/- 5cm, and vertical errors around +/- 10cm. Additional positioning error may be added due to timing differences between the sensor data stream and GPS data stream, and also the unavoidable error caused by sensor motion during the time window for each data point when signals are integrated. We have found that these errors create multiple local minima in the parameter space of our models, and we have investigated performance of alternative inversion schemes in terms of computation requirements and ability to find global minima. The downhill simplex, simulated annealing, and exhaustive search methods are applied to test data and to field data, and results are compared.

This work was funded by SERDP project CU-1121.

Presented at the SERDP/ESTCP Partners in Environmental Technology Technical Symposium & Workshop, November 28-30, 2000, Arlington, VA.

ELECTROMAGNETIC INDUCTION SPECTROSCOPY FOR LANDMINE IDENTIFICATION

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ABSTRACT

An estimated 110 million landmines, mostly antipersonnel mines laid in over 60 countries, kill or maim over 26,000 people a year. One of the dilemmas for removing landmines is the amount of false alarms in a typical minefield. Broadband electromagnetic induction spectroscopy (EMIS), however, is a promising technology that can both detect and identify buried objects as landmines. By reducing the number of false alarms, this approach significantly reduces costs associated with landmine removal. Combining the EMIS technology and a broadband EMI sensor, the scientific phenomenology that has potential applications for identifying landmines, unexploded ordnance, and hidden weapons at security checkpoints can now be explored.

Presented at the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Arlington, Virginia, February 20-24, 2000; Conference Proceedings, pp. 801-809.

Processing Techniques for Discrimination Between Buried Unexploded Ordnance and Clutter Using Multisensor Array Data

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This project addresses the issue of discriminating between buried unexploded ordnance (UXO) and clutter in the context of environmental cleanup. In spite of the recent advances in UXO detection performance, false alarms due to clutter (signals incorrectly diagnosed as having been caused by UXO) remain a serious problem. With traditional survey methods, the Army Corps of Engineers finds that 85-95% of all detected targets are not UXO. Since the cost of identifying and disposing of UXO in the United States using current technologies is estimated to range up to $500 billion, increases in performance efficiency due to reduced false alarm rates can result in substantial cost savings.

Typical ordnance items have certain distinctive attributes that distinguish them from clutter. They have a characteristic shape (long and slender) and their composition is distinctive (typically comprising a steel body with a brass or aluminum fuze body and copper driving bands or an aluminum fin assembly). Our experience is that these attributes correspond to distinctive signatures in magnetic and electromagnetic induction sensor data. Current research activities are directed towards exploiting differences in shape between ordnance and clutter with commercially available sensors. In this project we systematically explore the performance improvements which are realized when additional distinguishing target attributes are included in the discrimination process. The technical objective is to develop a reliable technique for discriminating between buried UXO and clutter using multisensor electromagnetic induction sensor array data.

During the first year we have developed a baseline model for the EMI signatures of simple slender objects (rods), and have established that the EMI signatures of ordnance items of comparable size and length-to-diameter aspect ratio differ in significant ways from the baseline.

Presented at the SERDP/ESTCP Partners in Environmental Technology Technical Symposium & Workshop, November 30 - December 2, 1999, Arlington, VA.

TARGET-SPECIFIC INFORMATION CONTENT IN BROADBAND EMI DATA

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ABSTRACT

Electromagnetic induction (EMI) occurs when a time-varying primary magnetic field is established over a buried conducting target. In response to the primary field, eddy currents develop within the target, producing a secondary magnetic field that can then be measured at the surface. The secondary field depends in part on specifics related to the identity of the target such as size, shape, composition, and orientation, but also in part on competing effects such as conducting soils, depth effects due to non-uniformity of the primary field, and inhomogeneous material properties within the target. These competing effects act to obscure some of the target-specific information, and it is therefore crucial to understand how much target-specific information is available in the raw data before any target identification scheme can go forward.

We present here results of controlled measurements made with the GEM-3 sensor to address this question. Several potential competing effects are evaluated and generally found to cause 1 percent or less deviation in the baseline signal for the objects tested. Generally, much larger differences were measured as a result of switching targets. In particular, the difference between a 37-mm shell and a sphere of roughly the same size was about an order of magnitude larger than any competing effect. The frequency-dependent structure of the difference was also reproducible and consistent over a range of depths. Therefore, we have established that this instrument is capable of delivering broadband EMI data with ample target-specific information content for the purpose of target classification and identification.

Presented at the SERDP/ESTCP Partners in Environmental Technology Technical Symposium & Workshop, November 30 – December 2, 1999, Arlington, VA.